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E. Trabert, P. Beiersdorfer

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Laboratory study supporting the interpretation of Solar Dynamics Observatory data

E. Träbert^{1,2}, P. Beiersdorfer¹

¹ Physics Division, Lawrence Livermore National Laboratory, Livermore, CA 94550-9234, U.S.A.

² Astronomisches Institut, Ruhr-Universität Bochum, D-44780 Bochum, Germany

E-mail: traebert@astro.rub.de

Abstract.

High-resolution extreme ultraviolet spectra of ions in an electron beam ion trap are investigated as a laboratory complement of the moderate-resolution observation bands of the AIA experiment on board the Solar Dynamics Observatory (SDO) spacecraft. The latter observations depend on dominant iron lines of various charge states which in combination yield temperature information on the solar plasma. Our measurements suggest additions to the spectral models that are used in the SDO data interpretation. In the process, we also note a fair number of inconsistencies among the wavelength reference data bases.

1. Introduction

In the Extreme Ultraviolet (EUV) and X-ray wavelength ranges, the Sun shows highly energetic and relatively short-term events. The *Solar Dynamics Observatory (SDO)* spacecraft [1] aims to study the dynamics of such events as well as the high variability of the overall EUV emission of the solar corona (which fluctuates by several orders of magnitude), combining high spatial resolution observations at a high exposure frequency with determinations of the actual plasma temperature in the range from 1 MK to 20 MK. The Atmospheric Imaging Assembly (AIA) experiment [2] on board the *SDO* spacecraft achieves these time-resolved observations in seven, mostly iron-dominated, EUV channels (centered at wavelengths 94, 131, 171, 193, 211, 304, 355 Å) with moderate wavelength selection by multilayer reflective optics. In combination and supported by extensive modeling [3, 4], the observations also yield the temperature in the solar coronal field of view. The seven AIA data channels have spectral band passes from 1 Å to about 20 Å wide. In parallel, a grating spectrograph of the Extreme ultraviolet Variability Experiment (EVE) [5] monitors the EUV spectrum with a band width of 1 Å.

The solar spectrum reflects the chemical composition of the Sun with elements at their natural abundances and charge state distributions depending on the local temperature. In the laboratory, the spectra of elements can be studied individually, and the charge state balance in a plasma can be adjusted. Hence it is possible to recognize the origin of spectral lines, possibly resolve spectral blends that originate from different elements, and to check spectral models for consistency.

Among terrestrial experiments, an electron beam ion trap (EBIT) offers the laboratory environment that is closest in density and working conditions to the solar corona. Various

elements of coronal interest (He, C, N, O, F, Ne, Mg, Si, S, Ar, Ca, Fe, Ni) are introduced into EBIT and ionized and excited by an energetic electron beam. The EUV spectra in the vicinity of the *SDO*/AIA observation channels are studied with spectrographs of resolving powers 1100 to 3000 (this spectral resolution is close to that of spectrographs on board of spacecrafts such as *Chandra* or *XMM-Newton*) and at various electron beam energies. We thus check the consistency and completeness of the spectral data that are used in the collisional-radiative modeling necessary for the interpretation of the *SDO*/AIA raw data, but with deliberate control over the elements introduced as well as the charge state distribution, and using a much higher spectral resolution than is available on board of the *SDO* spacecraft.

We mainly compare our observations with the NIST on-line data base [6] and with the CHIANTI data base (v. 7.1) [7]; the latter compiles wavelength data mostly from solar observations and models the relative line intensities. We note quite a number of inconsistencies among the wavelength reference data tables. Overall, the CHIANTI wavelengths are better compatible with our observations of the three (out of six) AIA iron channels covered so far. However, in our work in progress [8, 9] we also find a number of spectral lines that may have been under-appreciated in the spectral models.

2. Experiment

The experiment was performed at the EBIT-I electron beam ion trap [10] at the Lawrence Livermore National Laboratory. The device has been optimized for spectroscopic studies of highly charged ions [11], including the study of spectra needed for diagnosing high energy density plasmas [12]. In an electron beam ion trap, a quasi-monoenergetic electron beam is compressed in the field of a superconducting magnet to a density near $5 \times 10^{11} \text{ cm}^{-3}$ [13]; the energetic electrons ionize and excite target atoms in an ultrahigh vacuum environment. Ionization can continue until the ionization potential of the charge state reached exceeds the beam energy. In practice the ion cloud established in the magnetic and electric fields of a Penning trap shows a charge state distribution that represents a balance of ionization and recombination processes. In our electron beam ion trap, most materials of interest are injected as gases or gaseous compounds. Since neutral material is continually supplied, the charge state distribution also comprises a fraction of low charge state ions.

Ionization, collisional excitation, and recombination lead to the population of excited levels and thus offer spectroscopic access. In the EUV we employ flat-field spectrographs with cryogenically cooled CCD detectors [14, 15] that exceed the resolving power of the grating spectrograph on board *SDO* by one to two orders of magnitude. The spectral range covered by the CCD camera is 15 to 20 Å wide and thus exceeds the widths of the AIA detection bands; while the AIA detectors treat each detection channel (with a multipixel image) as a single wavelength band and the EVE spectrographs take spectra of 1 Å line width, our CCD camera offers 1340 pixels along the wavelength axis and a linewidth of 2-3 pixels. For each injected gas (CO₂, N₂, SF₆, Ne, Ar, ironpentacarbonyl, nickelocene, and so on) spectra were recorded at several electron beam energies from 200 to 1000 eV; for Fe and Ni further exposures reached to about 2000 eV. This procedure enabled a rough estimate of the charge state range of emitting ions as far as the electron beam energy surpassed the respective production thresholds (the ionization energies of lower charge states). All spectra contained emission from low charge states, because neutral gas was bled into the trap continually.

3. Wavelength calibration

The advantageous high resolution and the width of the field-of-view of the camera also imply limitations. Calibration lines are needed within the field-of-view of each spectrograph setting. The high-resolution spectrograph of ours offers a spectral slice with width of 17 to 22 Å, but not each element of interest has sufficiently many, intense, and accurately established lines

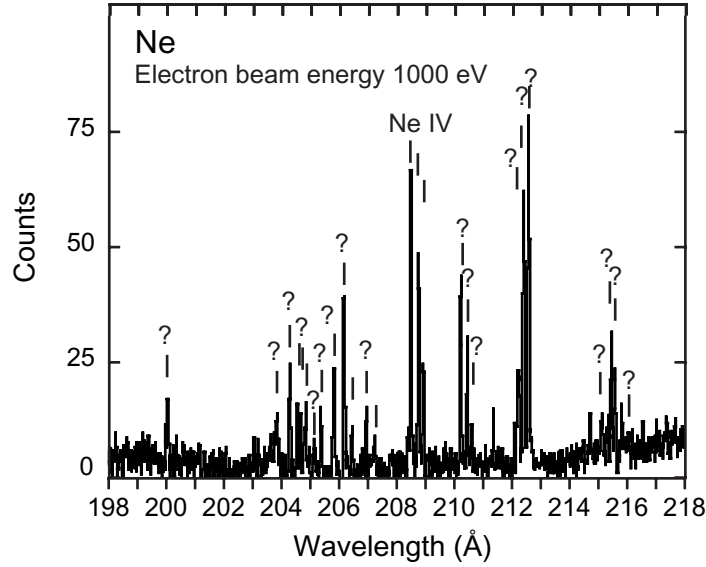


Figure 1. EBIT spectrum of Ne in the vicinity of the SDO/AIA 211 Å band. Only three of the Ne lines are known from the literature (NIST on-line data base and CHIANTI). The newly found and as yet unidentified Ne lines carry question marks.

in the proper charge state range. Hence our wavelength calibrations are based on sequential observations of several elements (C, N, O, F, Ne, Mg, Si, S, Ar, Ca, Fe, Ni). The combination of individual data sets yielding an average (slightly quadratic) calibration curve. Fortunately, lines of oxygen, which is an indigenous background material in EBIT-I, appear in many of the spectra we measure. Such lines then tie the individual data set to the wavelength reference scale.

Let us discuss Ne spectra as an example. Reliable reference lines are often scarce; from historic measurements of light elements, one would expect the best reference data from ions such as those of O, F, or Ne (see [16]). Low charge states are easier to produce in most light sources, but the spectra of few-electron ions are more easily systematized. The lighter ions usually have fewer spectral lines within a given wavelength interval, which renders line identification relatively simple. However, even the spectra of the lighter ions are incompletely known, as we explain for the case of Ne. Near 94 Å (one of the AIA channels), neon has lines of various charge states, and some of these lines also appear in second diffraction order and then appear near 196 Å, useful for calibrating the spectra in the vicinity of the 193 Å AIA channel [17]. The question is, how accurate the lines are as references. This matters not only for the present laboratory astrophysics work. For example, neon lines are highly relevant for the calibration in our ongoing measurements on Li- and Be-like ions of specific isotopes of rare earth elements (such as $^{141}_{59}\text{Pr}$ [18]) in which an insufficient calibration accuracy precludes highly accurate measurements of the Lamb shift.

Tondello [19] has obtained Ne lines in the EUV with error bars of 5 to 20 mÅ. Many of the Kelly and NIST data entries on Ne have been contributed by Hermansdorfer [20], whose study summarily assumes an uncertainty of up to ± 50 mÅ. Kramida over the years (in a variety of publications, for example [21, 22, 23]) has revised data on multi-electron level systems most of which now are estimated to be known to ± 20 mÅ, but this is not really good enough for calibrating accurately. Transitions in H-like ions have been calculated with practically perfect accuracy by Garcia and Mack [24]. Transitions in lighter He-like ions have been calculated to within 1 mÅ [25], and some lines in C and N (but not Ne) have been measured to such a

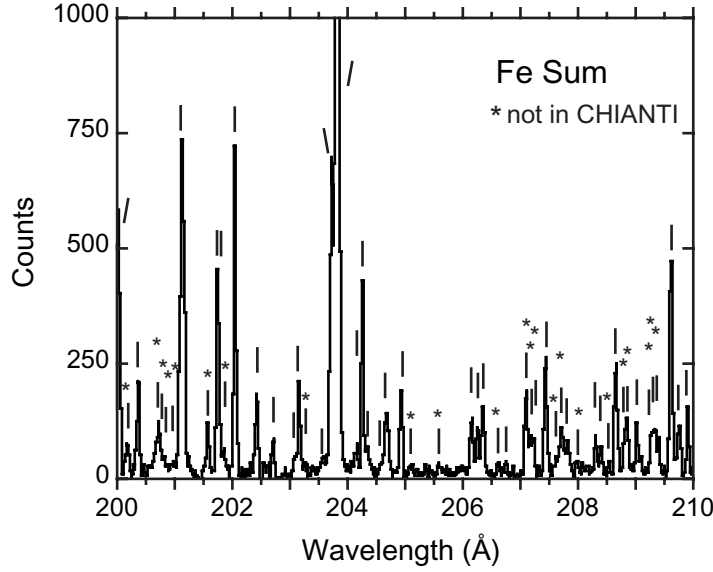


Figure 2. Sum of EBIT spectra of Fe recorded at various electron beam energies in the vicinity of the SDO/AIA 211 Å band. While most of the stronger Fe lines are identified, the lines marked with an asterisk are not listed in the CHIANTI data base.

low uncertainty [26]. However, most of the neon lines that are listed in the literature of the neighbourhood of the seven SDO/AIA bands belong to charge states 2+ to 8+, and none of them are known with such high accuracy. Actually, some 90 Ne lines are expected from the NIST and CHIANTI tables (taking the low density in an electron beam ion trap into account which lets most ions decay to the ground state) in the neighbourhood of the seven AIA bands, but only about 60 of these are seen in our EBIT spectra. Of the predictions, about 40 lines appear in only one of the two tables and not in the other. Some 60 Ne lines are seen in our EBIT spectra that have no equivalent in the tables. In the special example of the 211 Å SDO/AIA band, three known Ne IV lines are seen in the EBIT spectrum as well as 26 unidentified Ne lines [9] (Fig. 1). The Ne wavelength listings of the two tables perfectly agree in some cases and differ by up to 80 mÅ in others. Evidently the lines with good agreement among the literature compilations may be adopted with higher confidence, but this agreement is not a guarantee of validity. Where the disagreement is obvious, a possible cause may be misidentification; the data adopted in the NIST tables usually are taken from individually calibrated studies addressing a given element (though there may be contaminations), while the solar data in CHIANTI are from a multi-element light source anyway, which may benefit from a common calibration but which does not imply intrinsic information on the actual elemental identification. The calibration inconsistencies carry through to the spectra of heavier elements. We began our calibration exercise with identifying lines in the literature that under EBIT conditions would be expected to be prominent. However, many of them turned out to be not prominent in the observed spectra, or appeared at wavelengths (based on the average calibrations mentioned above) that were equally different from the various literature data and did not clearly favor the NIST or CHIANTI compilations throughout (though the latter seem more reliable overall). Consequently most of our line positions are limited in precision by statistics and in accuracy by the calibration problem, combining to 10 to 20 mÅ in most cases.

The complexity of the spectra causes identification problems. The charge states of elements Fe and Ni that are of particular interest feature an open $n=3$ valence shell, with a multitude

of lines. Around 200 Å, Fe has many more than just one line per 1 Å interval (see the sample spectrum in Fig. 2). In order to identify known lines, the wavelength calibration has to be much better established than 0.1 Å. Similarly, calculations of wavelengths that are not better than 100 mÅ may be easy to obtain, but are largely useless in practice. In the present study, parts of the Fe spectrum are so crowded with spectral lines that other elements would be difficult to recognize, unless their relative abundance exceeds the natural one. Fe is the element with the ninth highest natural abundance. Most elements beyond H, He, C, N, O, Ne, Mg, and Si are clearly less abundant and thus their spectra are correspondingly less bright in the Sun, and their lines are progressively difficult to discern in the presence of line-rich Fe.

In other words, the present example of Ne reveals many previously unknown lines of Ne in the vicinity of the SDO/AIA 211 Å band. Although Ne is more abundant than Fe in the Sun, the Ne lines in this band are likely hidden in the solar spectra by the dense line forest of Fe. However, now knowing that Ne has these lines that are not yet listed in models such as CHIANTI points out the necessity for refining the model, so that the pedestal under the Fe lines can be treated more correctly in the interpretation of the SDO observations. For this step it is not necessary to know accurately the wavelengths of the various Fe or Ne lines, or the many other contributions. When aiming at a more reliable detailed description of the solar spectrum and its contributions from many elements, this level of detail matters and brings back the problem of wavelength calibration.

4. Discussion

The CHIANTI data base is consistent in the sense that wavelength measurements of various elements refer to the same sets of observations, even as the individual line assignments face the usual problem of elemental identity as well as the atomic structure assignment. The NIST data base has been compiled from measurements that target individual elements. This is advantageous for the assignment of spectral lines to a given element, but then the data are archived and let rest with their often incomplete spectral coverage.

CHIANTI aims at understanding the solar spectrum and thus the team seeks to complete and update the data base frequently. However, elements that are not abundant in the solar spectrum are of little interest in this process, which probably explains why various elements and ions are apparently not represented in CHIANTI, although the associated calculations should be able to yield tables with fairly accurate wavelengths also for those ions. Our measurements indicate such gaps near the seven EUV bands studied by the SDO spacecraft. At the same time our measurements depend on previously measured lines in the very same spectral ranges that can be used for calibration, and there we find that the quality of the available data is not always as high as would be desirable.

Nonetheless, our investigation reveals a number of cases in which the modeling of the (spectrally much less resolved) solar signal of the seven AIA data channels should benefit from the inclusion of additional spectral lines that we identify. Hence the reliability of the interpretation of the SDO data for establishing a temperature scale can be expected to improve.

5. Acknowledgements

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